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Research Article

Impact of LQI-Based Routing Metrics on the Performance of a One-to-One Routing Protocol for IEEE 802.15.4 Multihop Networks

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The quality of an IEEE 802.15.4 link can be estimated on the basis of the Link Quality Indication (LQI), which is a parameter offered by the IEEE 802.15.4 physical layer. The LQI has been recommended by organizations such as the ZigBee Alliance and the IETF as an input to routing metrics for IEEE 802.15.4 multihop networks. As these networks evolve, one-to-one communications gain relevance in many application areas. In this paper, we present an in-depth, experimental study on the impact of LQI-based routing metrics on the performance of a one-to-one routing protocol for IEEE 802.15.4 multihop networks. We conducted our experiments in a 60-node testbed. Experiments show the spectrum of performance results that using (or not) the LQI may yield. Results also highlight the importance of the additive or multiplicative nature of the routing metrics and its influence on performance.

1. Introduction

The IEEE 802.15.4 standard [1, 2] specifies the Physical layer (PHY) and Medium Access Control (MAC) functionality of a Low-power, low-rate Wireless Personal Area Network (LoWPAN) technology conceived for a wide variety of control and monitoring applications. IEEE 802.15.4 is primarily targeted at simple and low-cost devices, including several types of embedded systems, sensors, and actuators.

IEEE 802.15.4 supports star and peer-to-peer topologies. The peer-to-peer topology is based on a multihop paradigm and is suitable for a plethora of scenarios, including industrial, agricultural, forest, urban, and vehicular environments, among others. For practical reasons, ad hoc, self-configuring, and self-healing routing functionality is commonly used in these application spaces [3–9].

The requirements for routing techniques in low-power environments are highly dependent on applications. Several routing protocols have been specifically developed for data-collection sensor networks [5–7], which are characterized by a many-to-one (or many-to-few) paradigm. Nevertheless, applications that exhibit one-to-one communication needs are gaining relevance. Some examples include interdevice communication in home automation, building automation and query and control in industrial, structural, and urban monitoring [3, 8, 9]. Many routing protocols that are currently used for this application space are descendants of the Ad hoc On-demand Distance Vector (AODV) routing protocol [10]. Examples of these are the mesh routing functionality of the ZigBee stack [4], the one-to-one mechanism of the IPv6 Routing Protocol for Low-power and lossy networks (RPL), which is being specified by the IETF ROLL Working Group (WG) [11], and other approaches found in commercial platforms and in the literature [12–15].

One of the key factors for network performance in a wireless multihop network is the routing metric. The consideration of link quality as an input to routing has proved to be a powerful approach in IEEE 802.11-based mesh environments [16, 17]. In the IEEE 802.15.4 context, many research efforts have already been devoted to link quality estimation [18–22]. Most of these efforts have focused on the link quality indication (LQI), which is a parameter offered by the IEEE 802.15.4 PHY. The aim of the LQI is to represent the quality of a link, as perceived by the receiver of a frame at the moment of frame reception. Hence, the LQI is a good candidate for consideration as an input to routing metrics. In fact, the ZigBee standard [4], the IETF 6LoWPAN WG [23], and recent proposals within the IETF ROLL WG [24] recommend its use. However, this approach has received little attention, with a few exceptions which did not focus on one-to-one routing [21, 25].

In this paper, we present an in-depth, experimental study on the impact of using the LQI in routing metrics for a routing protocol based on AODV, which is called Not So Tiny-AODV (NST-AODV) [26]. The experiments conducted show the spectrum of performance results that using (or not) LQI-based metrics may yield and allow to derive guidelines for the design of LQI-based routing metrics. While our work focuses on NST-AODV, we believe that the study will contribute to understanding the influence of LQI-based routing metrics on other routing approaches.

The remainder of the paper is organized as follows. Section 2 gives an overview of the routing protocol used in our experiments. Section 3 reviews link quality estimation techniques in low-power wireless networks. Section 4 surveys the main link quality-based routing metrics for the same environments. Section 5 describes the 60-node testbed used in this work. Section 6 presents an experimental characterization of the LQI parameter and discusses the use of LQI for routing metrics. Section 7 evaluates the performance of NST-AODV using the Hop count metric and three LQI-based routing metrics, which were selected from those examined in Section 4: (i) PATH-DR [21], which is aimed at choosing the paths with the maximum delivery ratio; (ii) the link quality-based metric for ZigBee mesh routing [4]; (iii) a metric called LETX, which aims to select the paths that require the minimum number of transmission attempts. Section 8 studies the performance of these routing metrics in the presence of background traffic. Finally, Section 9 concludes the paper with the main remarks and a discussion of future work.

2. Routing Protocol

The routing protocol we consider in our study is NST-AODV, an adaptation of AODV for IEEE 802.15.4 environments. This section first provides background on AODV. Then, it summarizes the particular features of NST-AODV.

2.1. AODV Overview. AODV is a reactive routing protocol. When a node requires a route, it initiates a route discovery procedure by broadcasting Route Request (RREQ) messages. Each node rebroadcasts RREQs, unless it has a valid route entry to the destination or it is the destination itself. In this case, it sends a Route Reply (RREP) message back to the originator node and ignores any subsequent RREQs that are transmitted through alternative routes. Backward or forward next-hop routing entries are created at each node that receives an RREQ or an RREP, respectively. Route entries expire after a specified time if the route becomes inactive (i.e., it is not used for data transmission). For each route entry of a node, there is a precursor list that contains the nodes that use this one as the next hop in the path to a given destination. The loop-freedom of routes towards a destination is guaranteed by means of a destination sequence number, which is updated when new information about that destination is received.

When a link in an active path breaks, the upstream node that detects this break may try to locally repair the route if the destination is close to the node. This is an optional mechanism. If local repair cannot be completed successfully or it is not supported, the node that detects the link break creates a Route Error (RERR) message, which reports the set of unreachable destinations. This message is sent to precursor nodes. Then, the source of the active path starts a new route discovery phase if a route to the destination is still needed. Data packets waiting for a route should be buffered during route discovery.

An AODV node that belongs to an active route may periodically broadcast local Hello messages for connectivity management. However, this approach may be expensive if nodes are battery-powered. Other strategies include link layer mechanisms. For example, unsuccessful layer two transmissions may be used as an indication of a link break for AODV. This method is known as Link Layer Notification (LLN).

2.2. NST-AODV. NST-AODV is a routing solution which was implemented in nesC language for devices running TinyOS [27]. It was developed on the basis of TinyAODV (Release 3) [28], to which several features were added to improve its reliability and to better support dynamic topologies [26]. The main characteristics of NST-AODV are summarized below.

(i) An LLN mechanism is enabled by default. This requires the protocol to run on top of the IEEE 802.15.4 reliable mode (where a node that correctly receives a data frame sends an acknowledgement frame to the sender).

(ii) After an unsuccessful link layer transmission, up to two additional retries triggered by layer three can be performed.

(iii) When a packet leads to link failure detection due to three consecutive, unsuccessful layer three transmission attempts, it is buffered and transmitted if a new route can be found. This may happen either if the node that detects the break is the originator itself or if it is an intermediate node that locally repairs the route.

The implementation consumes 957 bytes of RAM and 4664 bytes of ROM. For a detailed comparison of NST-AODV and other routing solutions, the reader can refer to the literature [26].

3. Link Quality Estimation in Low-Power Wireless Networks

Wireless communications suffer from a plethora of phenomena that make correct reception of transmitted data an uncertain event in many cases. Ideally, a routing protocol for a wireless multihop network should favor the use of good-quality links. The quality of the link between a sender and a receiver is generally modeled by the probability of successful frame transmission of that link. We denote this probability the Link Delivery Ratio (LDR). The main techniques for estimating link quality in low-power networks can be classified into (i) packet-based techniques and (ii) radio hardware-based techniques. Recent studies have experimented with combinations of both techniques [22].

3.1. Packet-Based Techniques. Packet-based approaches estimate the LDR (or related performance metrics) of a link by computing the ratio between the number of received and expected packets during a given time window. There are two main options for implementing this scheme: (i) active techniques, in which control packets are transmitted for this purpose [29, 30] and (ii) passive techniques, also known as snooping, in which data packets are assumed to use sequence numbers, and nodes keep track of the number of lost messages during a given time interval [4, 5, 31]. Despite their benefits, these two approaches require time and state to produce a result [19, 20, 31]. Furthermore, the first one may lead to additional energy consumption.

3.2. Radio Hardware-Based Techniques: LQI versus RSSI. To overcome the time and state limitations of existing schemes, many researchers considered the use of PHY parameters from off-the-shelf radio hardware [18–21]. Many radio chips that implement proprietary radio technologies provide the received signal strength indicator (RSSI), which is the strength of a received radiofrequency (RF) signal. Furthermore, IEEE 802.15.4-compliant radio chips, like the widely used Chipcon CC2420 [32], also offer the LQI. As defined by the standard, measurement of the LQI may be implemented by means of receiver energy detection, signal-to-noise ratio estimation, or a combination of these methods [4].

The CC2420, which has become the de facto IEEE 802.15.4 radio chip, measures the RSSI based on the average energy level of eight symbols of the incoming packet. Since the use of RSSI to calculate the LQI may lead to spurious quality indications, the CC2420 chip also provides a correlation value that is based on the first eight symbols of the incoming packet. This correlation value is in the range of 50 to 110, where 50 corresponds to the lowest quality frames detectable by the chip and 110 indicates a maximum quality frame. According to the standard, the LQI value is represented by one byte. For this reason, Chipcon suggested the use of a linear conversion of the correlation values into a range of 0 to 255, using empirical methods based on Packet Error Rate (PER) measurements. In addition, the LQI value may be obtained by combining the correlation and RSSI values. However, the LQI values have been assumed to be the correlation values in the relevant literature, without the range conversion [18–21].

Table 1: Summary of experiment results reported in various papers.

Work	Correlation coefficient	
	Average LQI and LDR/PER	Average RSSI and LDR/PER
[17]	0.73	0.43
[25]	0.90	0.56
[34]	0.80	0.55

Since the advent of CC2420, many efforts have been devoted to the comparison of the LQI and the RSSI as parameters for link quality estimation under different conditions [16–19, 25, 33]. All these studies agree that the average LQI has a greater correlation with LDR or with the Packet Error Rate (PER) than the RSSI. Table 1 summarizes some of the results.

These results are reasonable, as several phenomena may increase the RSSI measured by the receiver, while they may reduce the actual link quality. Some examples are the superposition of multipath components arriving from different paths [19] and the presence of narrowband interference [32]. Consequently, we will use the LQI for link quality estimation.

4. Link Quality-Based Routing Metrics for Low-Power Wireless Networks

This section surveys the most relevant link quality-based routing metrics that are suitable for low-power wireless networks. Routing metrics based on other principles (e.g., energy-aware ones) are outside the scope of this paper. For comparison purposes, the Hop count metric is included in the survey. We are interested in selecting a set of link quality metrics that fulfil the following requirements: (i) they can be implemented easily, based on the LQI; (ii) they are appropriate for the nature of NST-AODV (i.e., they do not require transmission of additional control messages); and (iii) they take into account the qualities of all the links of a path in the computation of the path cost.

4.1. Hop Count. Hop count was the default routing metric of the first routing protocols for wireless (and wired) networks. This metric is simple, which is an interesting property for networks composed of constrained devices. If the quality of all links in the network is the same, the Hop count metric selects the best paths. Unfortunately, real networks are typically composed of links of varying quality. Hence, this metric favors the use of short paths (in hops), even if these paths may offer poorer performance than longer paths of higher quality.

4.2. Shortest Path with Link Quality Threshold. The metric defined as SP(t) [5] is based on a shortest path (i.e., hop count) approach that excludes links whose quality is below a threshold t. Link quality is estimated using snooping techniques. This metric avoids the use of bad quality links, but it does not distinguish the quality of the links that are considered for path selection.

4.3. Link Quality Routing. One of the first attempts at routing based on link qualities in a low-power wireless network [35] was carried out using the Destination Sequenced Distance Vector (DSDV) routing protocol [36]. The quality of a link was obtained as the minimum snooped Path Delivery Ratio (PDR) in each direction between a pair of nodes. To calculate the link cost, each link quality was categorized into one of four classes. Then, it was converted into a link cost by transforming the average PDR of the corresponding category to the log scale, and then normalizing to the integer domain. The path cost was calculated as the sum of the costs of the links that compose the path. As adding link costs is equivalent to multiplying the packet delivery rates of each link, the principle behind this routing metric is to maximize the PDR. However, the computation of the link cost leads to a loss of accuracy of the metric.

4.4. ETX. The expected transmission count (ETX) metric [17] was one of the first attempts to increase performance in high rate (e.g., IEEE 802.11-based) wireless mesh networks, as an alternative to the Hop count metric. ETX estimates the expected number of transmissions of a packet through a link. This metric has been widely adopted in such environments, as a node only needs to compute the packet error probability in transmission and reception, denoted as d_f and d_r in (1), respectively. Both link directions are considered, since layer two acknowledgment-based Automatic Repeat reQuest (ARQ) mechanisms are used in many technologies. The cost of a path is the sum of the ETX values of the links of the path. Hence, the ETX metric aims to select the path with the smallest number of total link layer transmission attempts, which favors the selection of high throughput paths, by using the link cost defined as follows:

$$\mathrm{ETX} = \frac{1}{d_f \times d_r}. \tag{1}$$

The computation of the ETX metric of a link is usually based on the periodic transmission of broadcast probe messages to neighbors and a count of the related replies in defined time intervals [17]. It is typically implemented with Hello messages [30, 37]. Low-power environments cannot afford to use periodic transmission of control messages at a certain rate, since this may lead to premature battery depletion. In some cases, ETX has been adopted as a mechanism for estimating link quality during specific training periods in many-to-one sensor network schemes [29]. In low-power networks, the same metric has been renamed as Minimum Transmission (MT) and implemented using snooping techniques, under the assumption of a minimum data transmission rate for each node to allow for a link quality estimation [5].

4.5. MultiHopLQI. One of the first attempts at a link quality estimator for a routing protocol based on the LQI was MultiHopLQI [6], which was actually an evolution of the aforementioned many-to-one scheme proposed in [5]. A path cost metric is computed as the sum of the link costs of the path. The cost of a link is inversely proportional to the LQI.

4.6. ZigBee Metric. The ZigBee specification defines a path-cost metric which is computed as the sum of the link costs of the path. Let $\phi(l)$ be an estimate of the LDR of a link l. The link cost, denoted by $C(l)$ of link l is defined as follows [4]:

$$C(l) = \begin{cases} 7, \\ \min\left(7, \mathrm{round}\left(\dfrac{1}{(\phi(l))^4}\right)\right). \end{cases} \tag{2}$$

In effect, the ZigBee specification provides implementers with two options for computing the link cost: (i) the link cost is always equal to 7 or (ii) the link cost is related to the reciprocal of the LDR of the link. The first option is equivalent to the Hop count metric. The second one, which hereafter we will refer to as the ZigBee routing metric, was designed to reflect the number of expected transmission attempts required to get a packet through on that link, which is actually emphasized, since the exponent in the formula is 4. In this case, cost values are integer numbers in the interval between 1 and 7, in which an ideal link has a link cost value equal to 1. A drawback of this second option is that, though the quality of each link of a path is taken into account, the round() function introduces quantification error, which may preclude the metric from achieving the best performance. Note that this error grows with the path hop count. Finally, the ZigBee specification does not mandate the method for computing the LDR estimation, but it suggests two options: the first one is based on counting received beacons and data frames and observing the appropriate sequence numbers; the second one is based on the use of average LQI, which is mentioned as "the most straightforward method" in the specification [4].

4.7. Hop Count While Avoiding Weak Links. The *hop count while avoiding weak links* metric aims to select the path with the smallest number of "weak" links, that is, links whose LQI is below a certain threshold value [38]. The metric is defined as follows. Let WL and HC denote the number of weak links and the hop count of a path, respectively. The route cost is a tuple of (WL, HC), which is ordered lexicographically. That is, the path with the minimum WL is selected by the metric. If more than one path has the same WL value, then the one with the smallest HC is chosen. This metric was proposed as an adaptation of AODV for LoWPANs.

The main drawbacks of this metric are that it does not distinguish the qualities of the good links of a path, and the fact that it may not take into consideration the hop count of a path.

4.8. MAX-LQI and RQI. In the MAX-LQI metric [21], the path with the best *worst link* is selected. This is the path with the highest minimum LQI over the links of the path. The formal definition of the metric is as follows. Let P be the set of available paths between the sender and receiver. Let p be a path such that $p \in P$. Let L_p be the set of links of the path p. The path p^* is selected as

$$p^* = \arg\max_{p\in P} \min_{l\in L_p} \mathrm{LQI}(l). \quad (3)$$

This metric was defined to enhance the performance of the adaptive demand-driven multicast routing (ADMR) protocol [39]. It was implemented using the LQI values of the control messages involved in the route discovery procedure.

Another metric, called the Route Quality Indicator (RQI), is equivalent to MAX-LQI. The RQI of a path is defined as the minimum LQI of the links of that path. The path with the greatest RQI between the sender and receiver is selected [40].

MAX-LQI/RQI is not an accurate metric, since it only considers the quality of the worst link of a path. It does not explicitly take into account the other characteristics of the path, such as the hop count or the LQI of the rest of the links.

4.9. PATH-DR. PATH-DR is a metric defined to select the path with the greatest PDR between a sender and a receiver [21]. This metric requires an estimation of the LDR of each link. It selects a path p^* as

$$p^* = \arg\max_{p\in P} \prod_{l\in L_p} \phi(l), \quad (4)$$

$\phi(l)$ was obtained as a function of the LQI values of the link l. The metric was also used for ADMR. The PATH-DR metric aims to choose the paths with the highest PDR, regardless of the number of hops. Note that the metric takes into account the quality of all the links of a path.

4.10. LETX. We introduce a routing metric called LQI-based ETX (LETX), which defines the link cost as follows:

$$\mathrm{LETX}(l) = \frac{1}{\phi(l)}, \quad (5)$$

where $\phi(l)$ is obtained as a function of the LQI of the link. The link cost is an estimate of the number of transmission attempts required for successful frame delivery in a link. The path cost is the sum of the link costs of the path. The metric takes into consideration the quality of all the links of a path.

Note that LETX has the same aim as ETX. However, ETX requires frequent (generally, periodic) transmission of control messages or data packets through all links in order to estimate the quality of those links. Hence, even if no data transmissions are carried out in a network, ETX requires a minimum amount of transmissions in the network. Instead, LETX relies on LQI-based LDR estimation, which can be done by using a single LQI value (as we argue in Section 6.3). This is adequate for a reactive routing approach (e.g., the one considered in this paper), because the LETX metric can be computed "on the fly" during route discovery, without additional transmission of packets for LDR estimation. We evaluate the performance of LETX for NST-AODV in this paper.

4.11. Summary of Link Quality Routing Metrics for Low-Power Wireless Networks. Table 2 summarizes the main features of the link quality-based routing metrics presented in this section. Packet-based estimation schemes are generally used in proactive approaches, since link quality can be estimated by measuring the reception rates of control messages. Reactive approaches exploit the use of the LQI values of the control messages involved in route discovery procedures. ZigBee, PATH-DR, and LETX routing metrics enable the calculation of the cost of a path, based on the LQI values of all links. Therefore, we chose to evaluate the performance of these LQI-based routing metrics for NST-AODV. Note that the PATH-DR metric was originally designed for a one-to-many routing protocol. However, it can easily be adapted to a one-to-one approach.

5. Testbed Description

We conducted an experimental evaluation of LQI-based routing metrics for NST-AODV on an indoor, two-dimensional wooden grid to which 60 TelosB motes [33] are attached. The size of the grid is 4.5 m × 8.1 m. The testbed can be considered a 6 × 10-node matrix, in which the distance between two consecutive motes is 0.9 m either in a row or in a column. The grid hangs from the ceiling of our laboratory with nylon strings, at a distance of 2.5 m from the ground and 0.5 m from the ceiling. We took advantage of the Universal Serial Bus (USB) interface of the TelosB motes to allow communication between them and a desktop. For this purpose, we designed a three-level tree topology USB network composed of active hubs and cables. Since the hubs are active, all the nodes are mains-powered, which prevents two undesired effects: (i) battery replacement of the nodes and (ii) a decrease in the transmission power of the nodes as the experiments are carried out. In particular, the prevention of the second effect ensures that the same conditions can be met at each node. Figure 1 shows a picture of the grid. Other testbeds which were developed with similar goals are MoteLab [41] and Mirage [34].

The TelosB motes use the Chipcon CC2420 radio chip, which operates in the 2.4 GHz band. The TinyOS version running in the motes for all the experiments was 2.1.1 and the IEEE 802.15.4 beaconless mode was used. The channel selected was number 26, since this minimizes interference with other systems operating in the same band (e.g., IEEE 802.11) [42]. In order to better understand transmission performance, all motes were positioned in the same way, since the TelosB antenna is not omnidirectional.

Table 2: Comparison of the main characteristics of routing metrics used in low-power wireless networks.

Routing metric	Properties of the metric				
	Hop count	Awareness of link quality	Quality of all links is distinguished	Link quality estimation method	Nature of the routing protocol
Hop count	Yes	No	No	—	—
Shortest path with link quality threshold [5]	Yes, (considers only good quality links)	Yes	No	Packet-based techniques	Proactive, one-to-one
Link quality routing [35]	Yes (implicitly)	Yes	Yes (quantification)	Packet-based techniques	Proactive, one-to-one
ETX [17]/MT [5]	Yes (implicitly)	Yes	Yes	Packet-based techniques	Proactive, one-to-one and many-to-one
MultiHopLQI [6]	Yes (implicitly)	Yes	Yes	LQI	Proactive, many-to-one
ZigBee (link quality) [4]	Yes (implicitly)	Yes	Yes (quantification)	Packet-based techniques/average LQI	Reactive, one-to-one
Hop count while avoiding weak links [38]	Only when considered paths have the same number of weak links	Yes	No	LQI	Reactive, one-to-one
MAX-LQI [21]/RQI [40]	No	Yes	No	LQI	Reactive, one-to-many
PATH-DR [21]	Yes (implicitly)	Yes	Yes	LQI	Reactive, one-to-many
LETX	Yes (implicitly)	Yes	Yes	LQI	Reactive, one-to-one

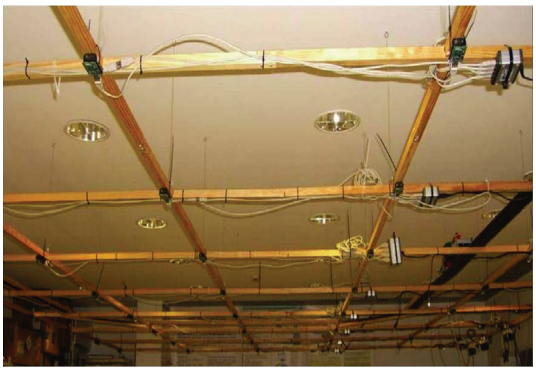


Figure 1: A picture of the testbed used in our experiments.

6. LQI Experimental Characterization

In this section we present an experimental study of the use of the LQI as an estimator of the LDR, to identify the potential advantageous and adverse characteristics of the LQI for its use in routing metrics. We also present and justify our LQI-based link quality estimation solution for NST-AODV.

6.1. Relationship between the LDR and the Average LQI. We conducted a set of experiments as follows. One thousand broadcast packets were sent from the mote at one corner of the grid. The number of packets and the LQI of each received packet were obtained at each of the remaining motes. The LDR was calculated for all the receivers. The same procedure was repeated three times, and the sender was placed at each of the other three corners, producing similar results. The transmission power was set at −25 dBm. Packets were transmitted at a rate of 3 Hz.

Figure 2 plots the LDR against the average LQI of each receiver. The results are consistent with those found by other researchers [20, 21]. Inspired by previous work [21], we obtain a piecewise linear model of LDR as a function of average LQI, which is also plotted in Figure 2. We will use this model to implement the metrics considered for evaluation in Section 7. However, as shown in Figure 2, the accuracy of the average LQI as a good estimator of the LDR varies depending on the quality of the link. Large and small average LQI values can be used to estimate the LDR with only a small degree of error. However, medium average LQI values are not as reliable. For instance, a link with an average LQI of 78.1 showed an LDR of 61.5% whereas another link with an average LQI of 78.2 showed an LDR of 94.5%. Note that, in some cases, the average LQI could overestimate the transmission performance by not including the LQI of lost packets [19].

6.2. Variability of the LQI of a Link. Figure 3 depicts the standard deviation of the LQI against the average values of

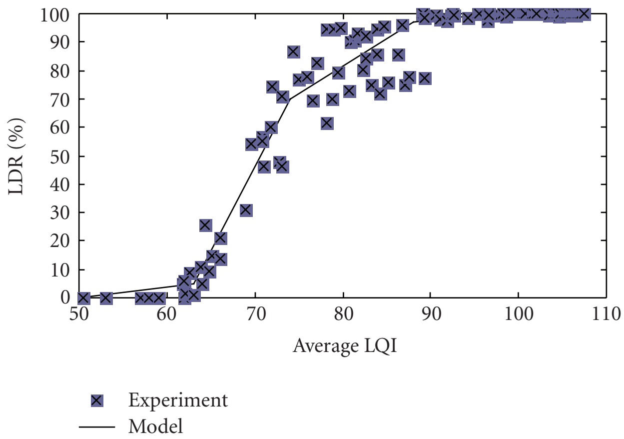


Figure 2: Plot of LDR against average LQI for each sender-receiver pair. A piecewise linear approximation model is shown.

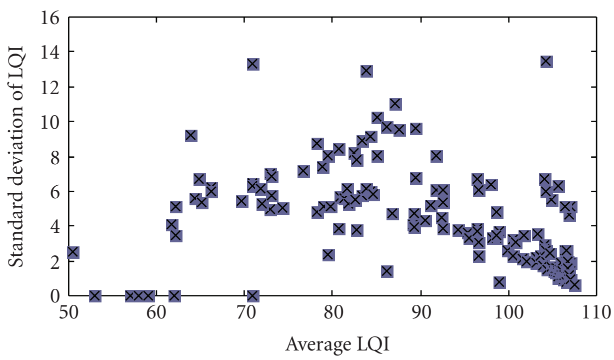


Figure 3: Standard deviation of the LQI against the average LQI values.

the LQI measured in each link. The LQI is almost constant for high average LQI values. For instance, the standard deviation is below 2 for average LQI values beyond 105 (which lead to LDR values between 99.9% and 100%). As the average LQI decreases, the standard deviation of LQI increases, to reach a peak value of 13.8 for an average LQI of 79.1. From this point, as the average LQI decreases further, the standard deviation of LQI exhibits a decreasing tendency, with greater scattering of the values than that shown on the right edge of the plot. The main conclusion from Figure 3 is that LQI is fairly constant with time for very high or very low link qualities, while it varies for medium link qualities.

Figure 4 further illustrates the LQI variation with time in four example links that show different LDR values. While the LQI is almost constant for a link with LDR = 100%, it exhibits large variations in a link with LDR = 77.4%. The range of LQI values obtained decreases as the link quality decreases, as shown in links with LDR = 48.0% and LDR = 13.7%.

Our results differ from those of a study which focused on the temporal characteristics of the LQI [19]. Authors of the cited work concluded that the LQI was stable with time and exhibited a maximum standard deviation of 1.2. The explanation is that their experiments were carried out in very good channel conditions, since an LQI between 103.1 and 107.0 was reported.

6.3. Considerations for Routing. Ideally, a link quality estimator for a routing protocol should be accurate, agile, and stable, and should add minimum overhead to the routing protocol. Below, we discuss the trade-offs in the fulfillment of the previous requirements when an LQI-based estimator is used.

The main drawback of an LQI-based link quality estimator is the fact that it may provide spurious link quality indications in a medium quality link. If such a link appears to temporarily exhibit better quality than the *steady state* one, any path containing this link may experience early problems (e.g., end-to-end connectivity gaps). In the opposite case, the link quality estimation mechanism might induce the path selection algorithm to select other worse performing links. Averaging techniques could reduce the impact of LQI variations, but some of these are slow to adapt to changes [20, 31]. Furthermore, as already shown in Subsection 6.1, even the average of a large number of LQI samples does not assure accurate prediction of the LDR in medium-quality links. Hence, averaging LQI may result unnecessary in this zone of link qualities.

On the other hand, LQI-aware routing favors the use of the available links with the highest quality, that is, those links with most temporarily stable quality characteristics. High-quality links exhibit high and relatively constant LQI values, suggesting that such links can be detected using a window of a single LQI sample. We investigated this possibility as follows. For each LQI sample from our experiments, we studied the probability of it corresponding to a link with a measured LDR greater than or equal to a given value. The results are plotted in Figure 5, which shows that a single LQI sample with a high value is a reliable estimator of a good quality link.

Finally, note that LQI-aware routing favors the use of high quality links, and hence tends to avoid the use of medium quality links (whose quality might in some cases be inaccurately estimated based on LQI). As will be shown in Section 7, adequate LQI-based routing metrics provide better performance than the Hop count routing metric.

6.4. Use of LQI for NST-AODV. In view of the previous observations, we designed a simple LQI-based route selection mechanism for NST-AODV as follows. During route discovery, each node that receives an RREQ message converts the LQI of that message into the estimated LDR, by applying the piecewise linear model shown in Figure 2. The estimated LDR of each link is then used to calculate the cost of the link, according to the routing metric used. The accumulated cost of the path is written in the RREQ before being rebroadcast and the destination sends a RREP through the route with the best cost. Once a path is found, the qualities of the links of the network are not sampled again until the selected path breaks, which leads to a new route discovery process. Note that this approach neither adds a control message overhead nor adds state at the nodes, in comparison with the use of the default NST-AODV (which uses theHop count metric).

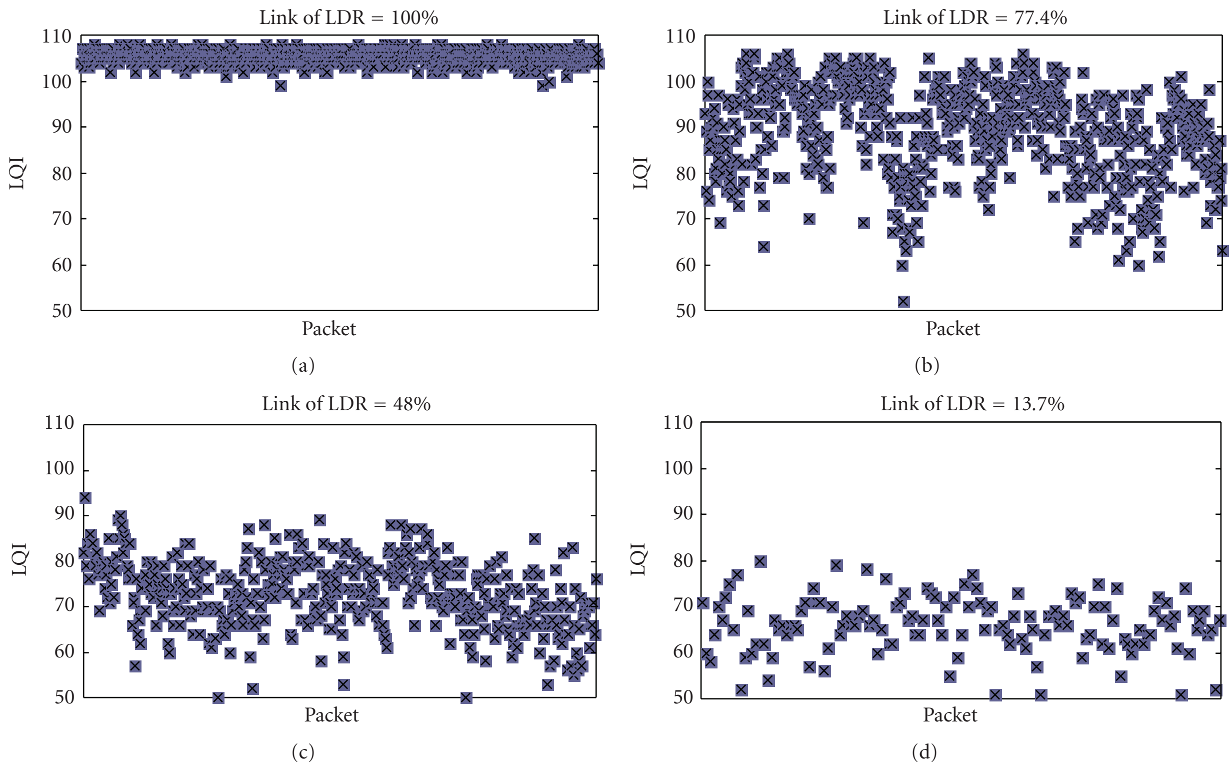


Figure 4: LQI values for links with different LDR: (a) Link of LDR = 100%, (b) link of LDR = 77.4%, (c) link of LDR = 48%, and (d) link of LDR = 13.7%.

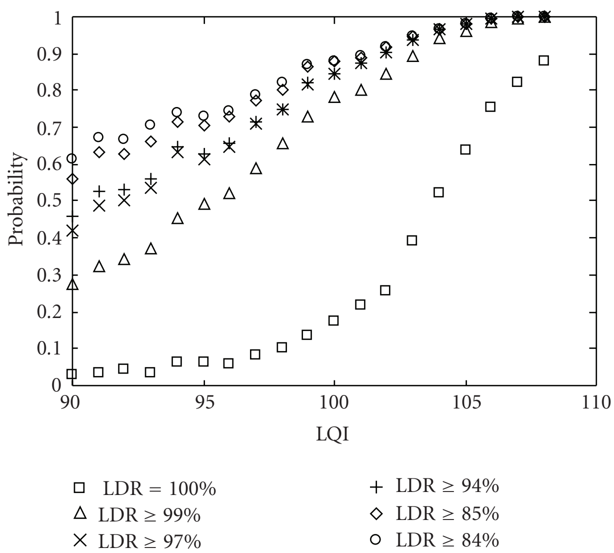


Figure 5: For each LQI value, the probability of corresponding to a link with an LDR greater than or equal to a given bound.

7. Experimental Comparison of Routing Metrics

This section presents the main part of the extensive set of experiments that we conducted to evaluate the performance of NST-AODV with the Hop count, PATH-DR, ZigBee, and LETX routing metrics. Since these metrics have different objectives, we expected to obtain the spectrum of performance results that the use (or not) of LQI in the routing metric may yield. As an additional contribution of the paper, the code in nesC of NST-AODV with the four routing metrics can be found in our website [43].

7.1. Definition of Experiments. The experiments were performed on the testbed presented in Section 5, with low presence of people in the laboratory. We forced multihop communications by setting the transmission power so that the maximum transmission range was 2 m (recall that the TelosB antenna is not omnidirectional). We investigated the influence of each routing metric on the following performance parameters: path hop count, path lifetime, PDR, and cost of data packet delivery.

In each experiment, 1000 packets were transmitted periodically at a rate of 3 Hz from a sender to a receiver, without any other concurrent flows. Thus, the obtained results were isolated from network congestion effects (the reader may note that Section 8 is a study on the influence of background traffic on the routing metrics). All the experiments were carried out for the four routing metrics considered.

In order to better understand the performance of each routing metric depending on the distance and relative position between sender and receiver, two different scenarios were defined, as shown in Figure 6. In the first one, the sender is a mote placed at one corner of the grid and the different receivers are the 28 motes in the two rows and columns that

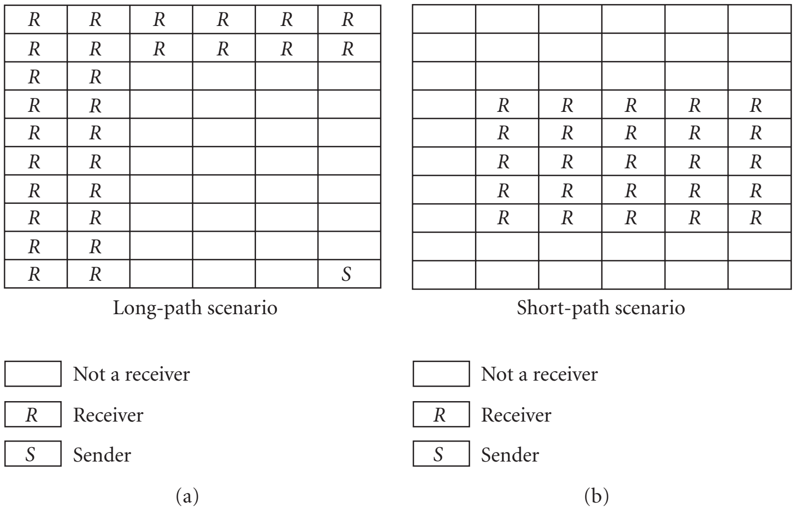


Figure 6: Long-path (a) and short-path (b) scenarios.

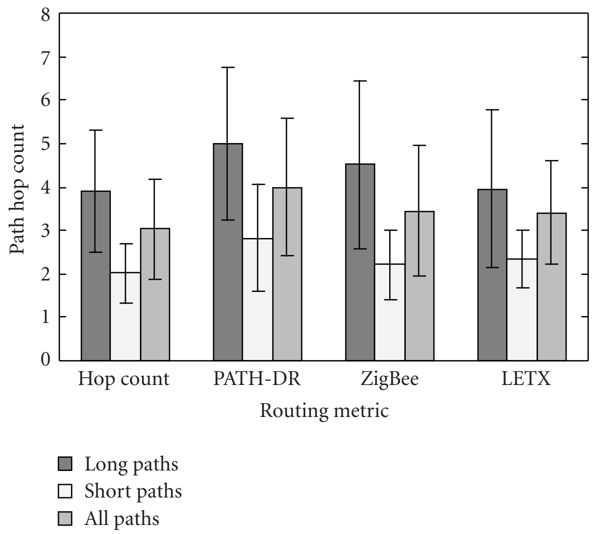


Figure 7: Average values and standard deviation intervals for the path hop count with each routing metric.

are furthest from the sender. In the second one, the receivers are the 24 motes closest to the sender. Hereafter, the first and second scenarios will be referred to as *long-path* and *short-path scenarios*, respectively.

7.2. Path Hop Count. We first study the hop count of the paths found in the experiments. Figure 7 depicts the average and standard deviation of the path hop count for each routing metric in the long- and short-path scenarios. Figure 8 illustrates the PDF of the path hop count for each routing metric. As expected, the Hop count metric selects the paths with minimum length in hops. However, the LETX metric, which takes into account link qualities, performs very closely to the Hop count metric in terms of path length. This is because the additive nature of the metric makes it similar to a Hop count metric for paths with good quality links. In contrast, the PATH-DR metric aims to select the paths with the highest PDR (see Section 7.4) and these paths are on average one hop longer, as shown in Figure 7. In the short-path scenario, the ZigBee metric exhibits a path hop count performance similar to that of LETX and the Hop count metric, because it is also an additive metric. However, in the long-path scenario, the ZigBee metric yields a greater path hop count than LETX. Although the ZigBee metric loses accuracy due to the quantification that it applies to calculate the link cost (e.g., a link of LDR = 85% has the same cost as a link of LDR = 100%), it tends to avoid bad links (see the exponent equal to 4 in (2)) and search for longer routes composed of good links.

7.3. Path Lifetime. The next performance parameter we study is path lifetime. We define path lifetime as the length of each period during which an end-to-end path does not suffer link failures. This performance parameter is relevant, since a link or path failure triggers routing protocol messages in many routing techniques and may lead to route changes. Furthermore, a stable topology should make higher-level operations, such as scheduling, aggregation [5], and transport layer protocols easier to design and implement. Recall that NST-AODV decides that a link has failed after three consecutive unsuccessful frame transmission attempts. Note that, although the motes in our testbed are static, link failures occur due to link quality changes because mote receivers are close to the signal-to-noise threshold [5, 21].

Figure 9 illustrates the average and standard deviation of path lifetime for each routing metric, measured as the total time between the instant in which a path delivers its first packet and the instant at which the last packet delivered by the same path reaches the destination. Figure 10 shows the CDF of path lifetime in the short-path and long-path scenarios, respectively. As shown in Figures 9 and 10, the paths selected by the Hop count metric suffer link failures earlier than the paths selected by LQI-based metrics. This occurs because the Hop count metric is insensitive to the quality

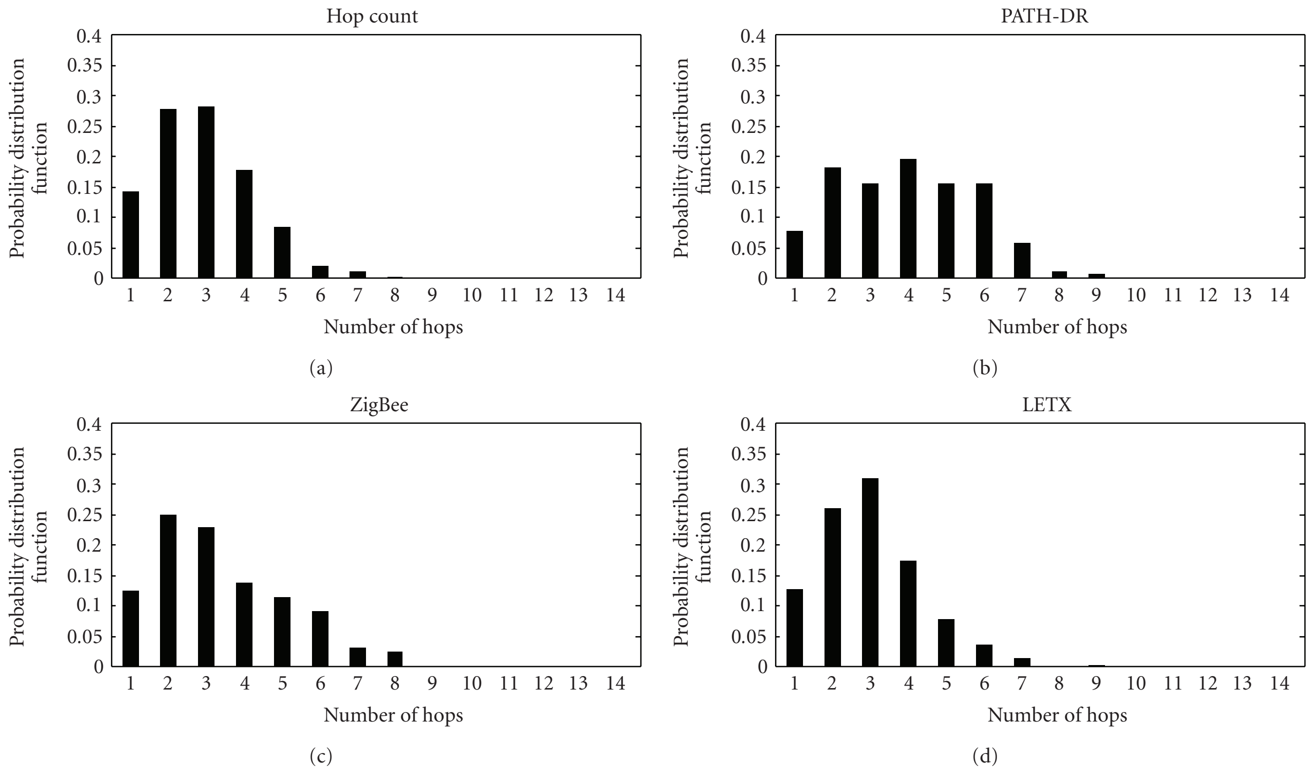


Figure 8: PDF of the path hop count for the routing metrics considered. The PDF is plotted on the basis of an analysis of all paths.

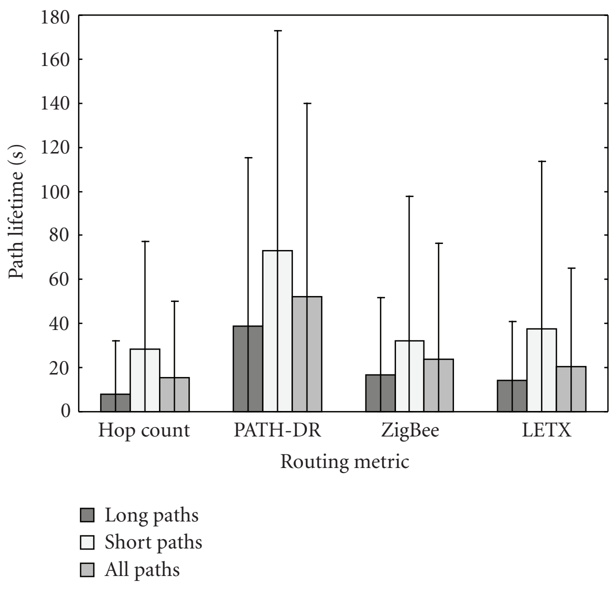


Figure 9: Average values and standard deviation intervals of path lifetime for the different routing metrics.

of the links in the network. In contrast, PATH-DR gives the largest path lifetimes. As this metric aims at maximizing PDR, it selects routes composed of good links. As shown in the previous subsection, this results in choosing many *safe* links (i.e., links whereby the receiving end operates well beyond the signal-to-noise ratio threshold) for communication between two nodes, rather than using a few fragile links. LETX and ZigBee are sensitive to link quality and therefore offer larger path lifetimes than the Hop count metric. However, they do not perform as well as the PATH-DR metric, due to their additive nature, which enforces a tendency to select short paths in number of hops and to use nodes which operate close to the signal-to-noise ratio threshold.

7.4. Path Delivery Ratio. The performance of a routing metric in terms of PDR in NST-AODV can be explained by the performance of the metric in path lifetime. The reason for this is that, after a path failure, a connectivity gap takes place, during which the protocol tries to find a new route for the data. The connectivity gap ends when the first data packet reaches the receiver after the path failure by using a new path.

Remarkably, the connectivity gap duration is independent of the routing metric (we measured an average connectivity gap duration of 1.7 s, which depends on the protocol settings and the data sending rate). The reason for this is that, after route discovery, the first route obtained by the sender (via the first RREP it receives) is used for data transmission. If better routes are found later (i.e., subsequent RREPs from the same route discovery reach the sender via better paths), these routes are used for the next data packets. Nevertheless, the first data packet transmission after route discovery is always carried out through the first available path, which does not depend on the routing metric used.

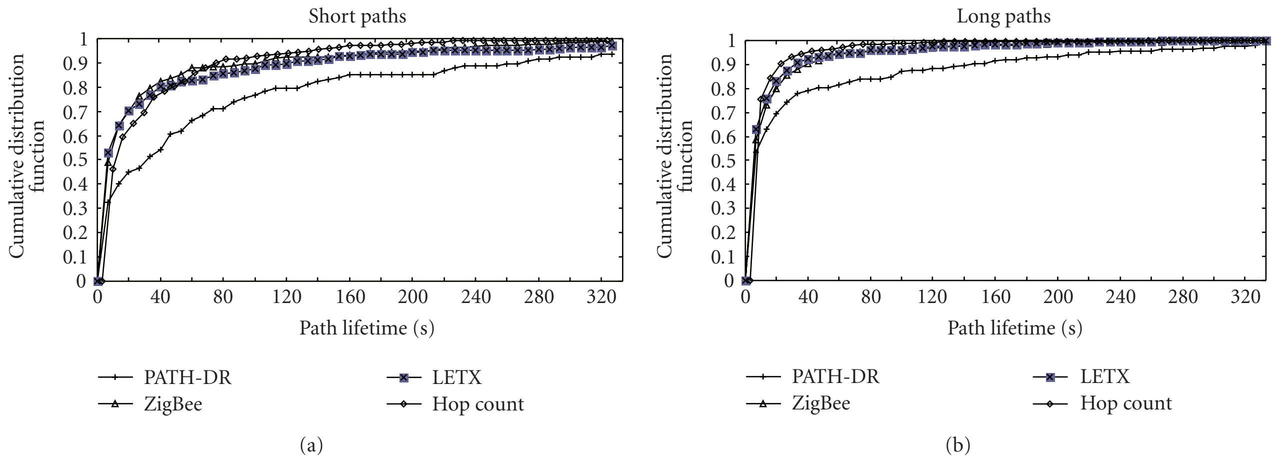


Figure 10: CDF of path lifetimes for the different routing metrics: short-path scenario (a) and long-path scenario (b).

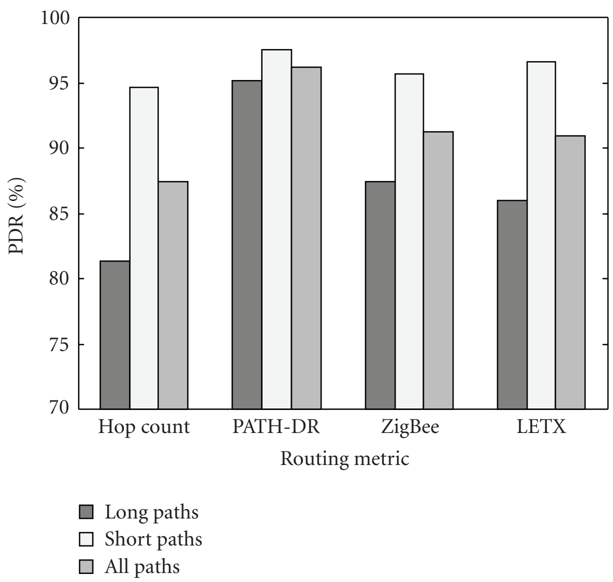


Figure 11: Impact of the routing metric on PDR.

Figure 11 illustrates the average PDR measured in the experiments with each routing metric. Figure 12 plots the CDF of the PDR of all the flows. The PATH-DR metric yields the highest PDR. This result is consistent with that expected theoretically, since the metric is specifically designed for this purpose. The overall PDR of PATH-DR is from 5.5% to 10.0% higher than that obtained with the rest of the metrics. LETX and ZigBee metrics yield greater PDR than the Hop count metric and provide similar performance, which can be explained by the similar behavior of these metrics in terms of path lifetime (see Section 7.3). The Hop count metric suffers frequent path failures and yields the lowest PDR among the considered metrics.

In the short-path scenario, the differences between the metrics in terms of PDR are small. The lowest PDR, which is given by the Hop count metric, is equal to 94.6% whereas PATH-DR provides the highest PDR, which is equal to 97.5.

In the long-path scenario, PATH-DR also obtains the best performance, with a PDR of 95.1%, whereas the Hop count metric provides only a PDR of 81.3%. As shown in Figure 12, in this scenario the differences between the performance of the metrics under consideration become clearer than in the short-path one.

7.5. Topological and Spatial Study. We next study the influence of the location of the sender and receiver on the measured PDR and path hop count for each routing metric.

7.5.1. PDR. Figures 13 and 14 depict the PDR measured at the receiver of each flow for the four routing metrics. As the physical distance between sender and receiver increases, the PDR tends to decrease, as expected. However, this tendency is not monotonical.

In fact, the quality of a route not only depends on the physical distance between sender and receiver, but also on how various factors affect the radio signal at the receiver of each link composing the route. One of these factors is multipath propagation (which is found in indoor and some outdoor scenarios), whereby the transmitted signal and its reflection on surfaces (e.g., walls, tables, ceiling, floor, etc.) reach the receiver by different physical paths. These signal components have different amplitudes and phases, and hence multipath propagation can lead to constructive or destructive interference. In the 2.4 GHz band, which is the one used in the experiments, the quality of the signal received by a node may vary significantly as the node's position changes by a few centimeters, because the signal wavelength is 12.5 cm [44]. Other factors that affect the quality of a given link include obstacle attenuation; the fact that the TelosB antenna is not omnidirectional [33], and even differences in radio hardware manufacturing. In consequence, the PDR that can be obtained for some receivers may be greater than the PDR obtained for other receivers which are physically closer to the sender.

Furthermore, LETX and ZigBee metrics contribute to the phenomenon mentioned above, as these metrics are not

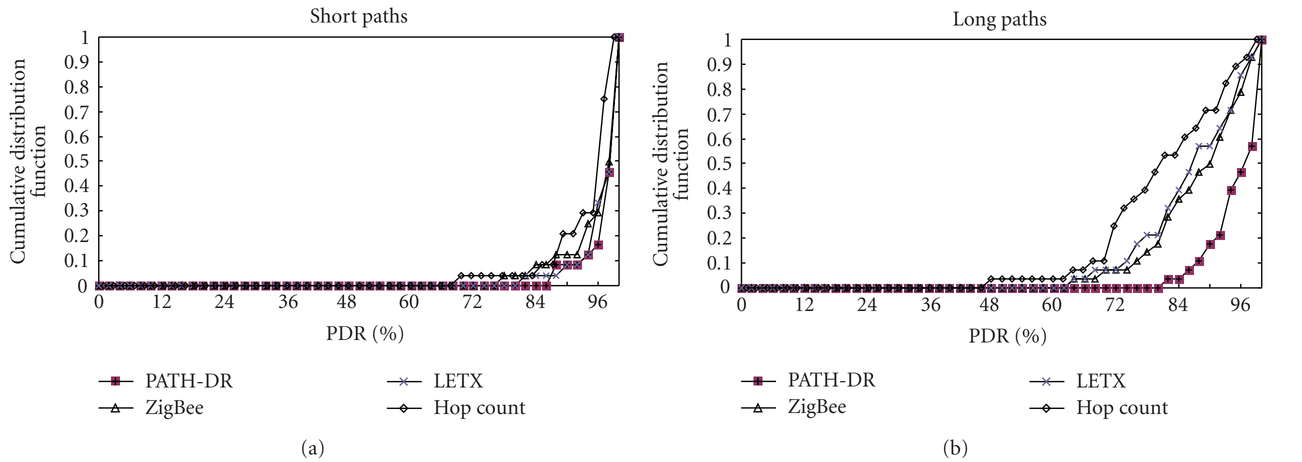


Figure 12: CDF of flows for different routing metrics with default routing protocol settings: short-path scenario (a) and long-path scenario (b).

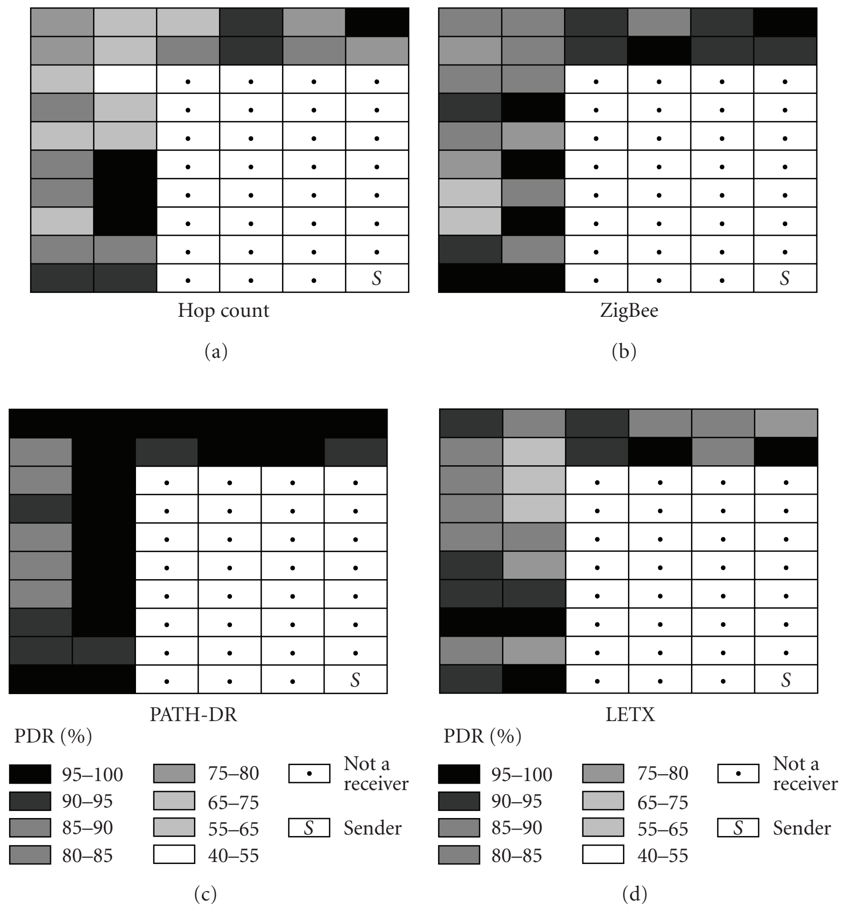


Figure 13: PDR for the Hop count, PATH-DR, ZigBee, and LETX metrics: long-path scenario.

intended to maximize PDR, and hence may select routes that offer a PDR below the maximum achievable for some nodes. Figure 15 illustrates an example of this behavior. The routes selected by LETX and ZigBee metrics from node A to nodes F and D are AEF and ABCD, respectively, which offer PDR values of 84% and 100%, respectively (i.e., PDR grows even if the distance to the destination grows, and nodes F and D are neighbors). Note that LETX and ZigBee discard the ABCDF path, which gives a PDR of 100%. This behavior may contribute to the fact that in Figure 14 (ZigBee and LETX), there

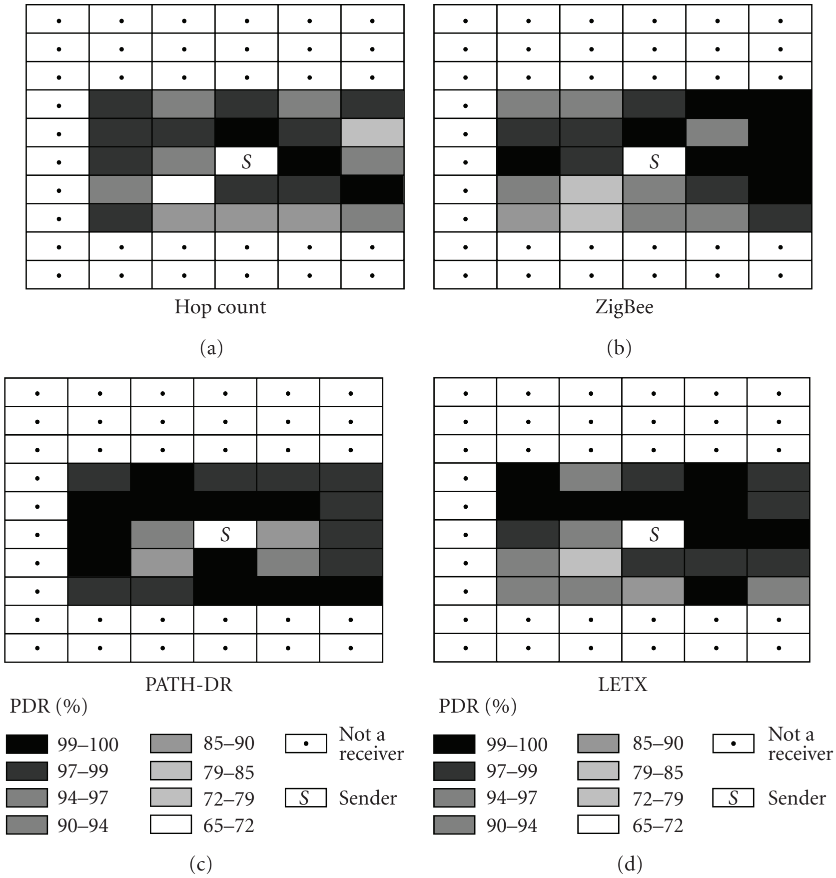
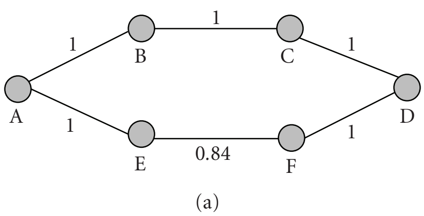


Figure 14: PDR for the Hop count, PATH-DR, ZigBee, and LETX metrics: short-path scenario.



	Hop count	PATH-DR	ZigBee	LETX
AEFD	3	0.84	4	3.19
ABCD	3	1	3	3
AEF	2	0.84	3	2.19
ABCDF	4	1	4	4

(b)

Figure 15: Example of route selection based on LETX and ZigBee metrics, whereby PDR grows as the distance between sender and receiver grows. The number placed next to a link indicates the LDR of that link. The shaded boxes indicate the cost of the path selected by each routing metric between node A and nodes D and F.

are nodes that obtain a PDR greater than 99%, and which are surrounded by nodes that obtain lower PDR values.

7.5.2. Path Hop Count. As shown in Figures 16 and 17, the average hop count of the flows does not monotonically increase as the distance between sender and receiver increases, due to the radio signal propagation issues mentioned in Section 7.5.1. Figure 18 plots the PDR of each flow against its average number of hops for the four routing metrics.

7.6. Cost of Data Packet Delivery. Finally, we study the influence of each routing metric on the cost of data packet delivery, defined as the average number of packet transmissions in the network per delivered data packet. Note that packet transmissions in the network include the transmission of AODV messages as well as data packet transmissions and retransmissions. We also test a Best-Effort (BE) approach for NST-AODV, in which only the initial route discovery takes place for a flow, and no data retransmissions are performed. Thus, we can evaluate how the routing metric affects the cost with the default and BE settings. The latter allows us to obtain a lower bound on the cost with NST-AODV, which can only be measured when the mechanisms of the protocol for connectivity maintenance and reliability are disabled. Of course, the cost benefits of this protocol variant are

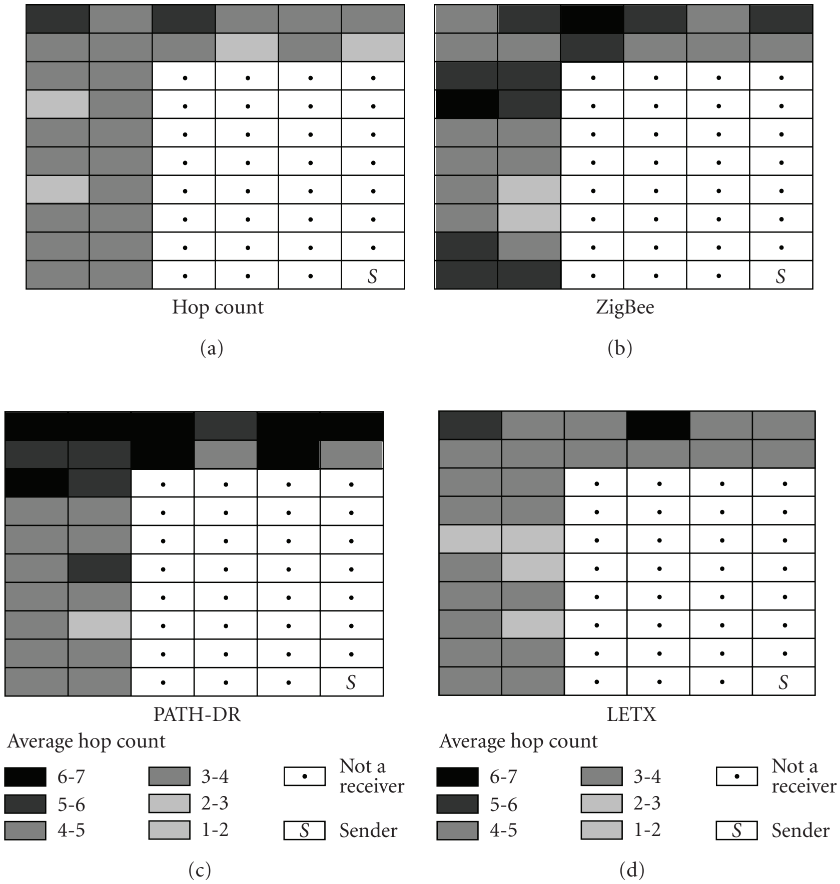


Figure 16: Average number of hops for the Hop count, PATH-DR, ZigBee, and LETX metrics: long-path scenario.

traded for PDR performance. With this version of the routing protocol, we measured an average PDR of between 51.9% (with the Hop count metric) and 62.9% (with the PATH-DR metric).

Figure 19 illustrates the cost using NST-AODV in its default and BE forms. In default NST-AODV, a link failure triggers a new route discovery. In consequence, the number of messages related with route discovery dominates the total number of transmissions in our experiments. PATH-DR yields the lowest cost because it leads to the minimum number of route discoveries per delivered packet among the considered routing metrics (note that PATH-DR provides the highest PDR). As shown in Figure 19, the number of data packet retransmissions is significantly smaller than the number of control messages (i.e., NST-AODV messages). In BE NST-AODV, the cost is dominated by the hop count of the paths. For this reason, the Hop count metric obtains the lowest cost with this protocol variant.

8. Performance of Routing Metrics in the Presence of Background Traffic

This section presents an experimental evaluation of the routing metrics under consideration in the presence of background (BG) traffic. First, we present a study on the sensitivity of the LQI to BG traffic. Then, we evaluate the impact of BG traffic on the performance of default NST-AODV with the routing metrics considered in Section 7. The radio chip settings for the experiments were those used in the previous section. In order to make sure that data transmissions were affected by BG traffic, the BG transmitters were set to broadcast packets continuously, that is, these transmission attempts could only be delayed by medium access contention. Note that these are severe background traffic conditions, which are unlikely to be found in real deployments, but which allow us to derive conclusions in a worst case scenario.

8.1. Sensitivity of the LQI to Background Traffic. We investigated the impact of BG traffic on the LQI of two different links, denoted Link 1 and Link 2, which offered good and moderate quality, respectively, in the absence of BG traffic. The sender and receiver of these links, as well as the BG traffic transmitters, are shown in Figure 20. Two scenarios were tested for each link. In scenario A (see Figures 20(a) and 20(b)), five different BG traffic configurations were tested for each link: (i) no BG traffic; (ii) all nodes labeled B1 transmitting simultaneously; (iii) all nodes labeled B2 transmitting simultaneously; (iv) all nodes labeled B3 transmitting

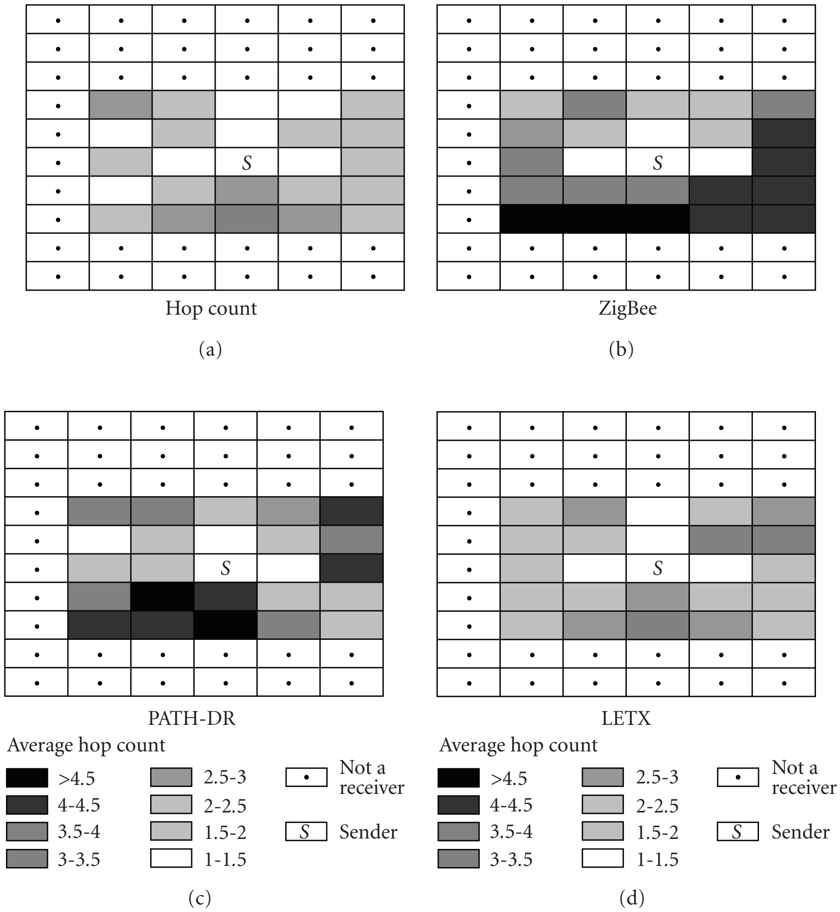


Figure 17: Average number of hops for the Hop count, PATH-DR, ZigBee, and LETX metrics: short-path scenario.

simultaneously; (v) all nodes B1, B2, and B3, transmitting simultaneously. In scenario B (see Figures 20(c) and 20(d)), four different configurations were considered: (i) no BG traffic; (ii) all nodes labeled B4 transmitting simultaneously; (iii) all nodes labeled B5 transmitting simultaneously; (iv) all nodes B4 and B5 transmitting simultaneously. Figures 21 and 22 depict the LQI and LDR results from five thousand data packet transmissions for each considered link in scenarios A and B, respectively.

As shown in Figures 21 and 22 (for Link 1), the LQI is sensitive to background traffic, but the decrease of average LQI, and the increase of LQI standard deviation with background traffic are low. However, LQI-based routing metrics may yield good performance, as the sensitivity of the LQI to background traffic accumulates over all the hops of a path (see Section 8.2). Note that, in Scenario B, Link 2 is severely affected by BG traffic and no packet is correctly delivered (and hence, no LQI values are obtained).

Finally, it is worth mentioning that when a contention-based MAC scheme is used (e.g., as in the beaconless mode, and in the Contention Access Period of the beacon enabled mode of IEEE 802.15.4), two phenomena may contribute to data packet loss in scenarios like the considered ones, due to background transmissions.

(i) If the RSSI measured by the sender during Clear Channel Assessment (CCA) is greater than the energy detection threshold, after the random backoff, the sender will wait for another random period before trying to access the channel again [1]. This procedure will be repeated up to a maximum number of times before a channel access failure is declared.

(ii) Otherwise, a background transmission will appear as interference at the receiver, which can corrupt the received data signal.

Whereas both phenomena may contribute to data packet loss, LQI is only sensitive to the second one. Nevertheless, the TinyOS 2.1.1 IEEE 802.15.4 implementation for the CC2420 radio chip does not limit the number of backoff periods for a sender in a transmission attempt. Due to this reason, the packet losses occurred during our experiments were only due to the second phenomenon indicated.

8.2. Impact of Background Traffic on the Performance of Routing Metrics. We carried out a set of data packet transmissions by using NST-AODV with the Hop count, PATH-DR, ZigBee, and LETX metrics in the presence of BG traffic. Figure 23 illustrates the sender, the three different receivers, and the BG transmitters used (which are denoted B1 or B2).

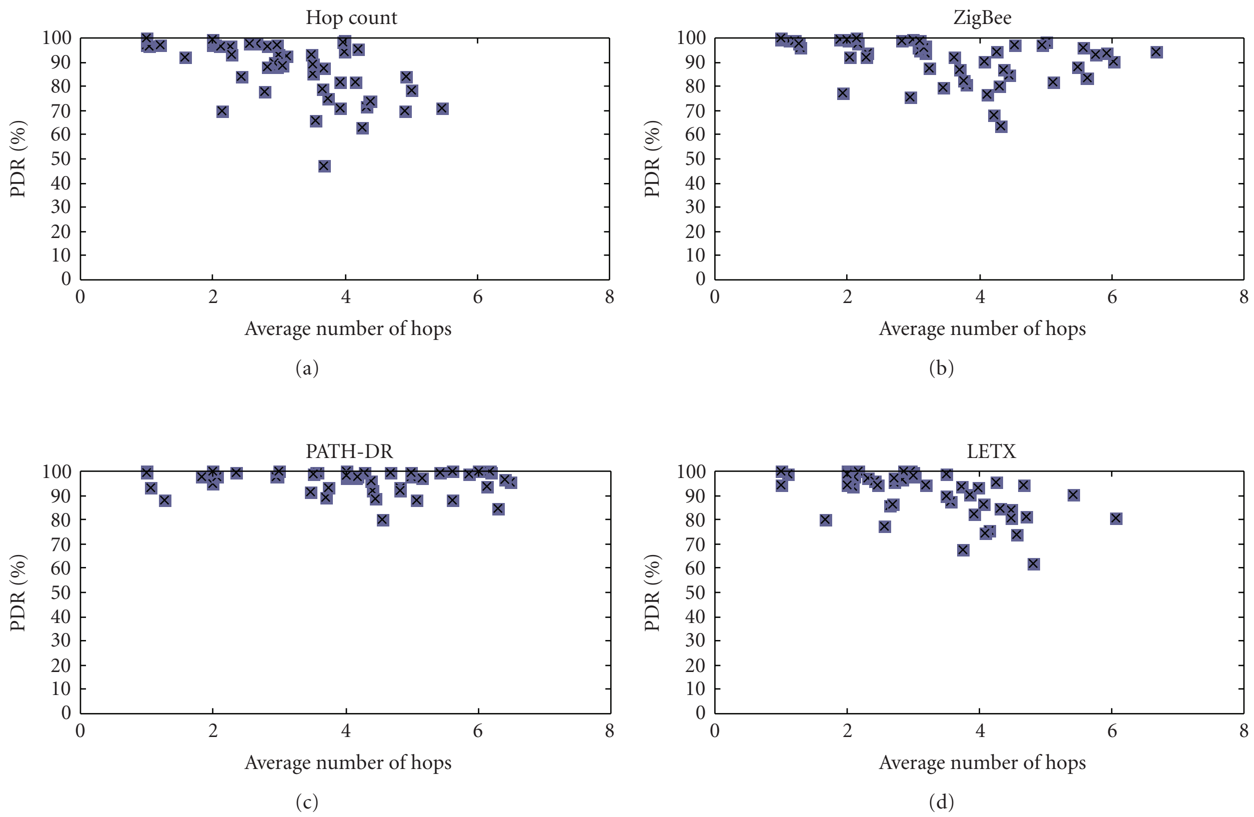


Figure 18: PDR as a function of the average number of hops, as measured in the experiments.

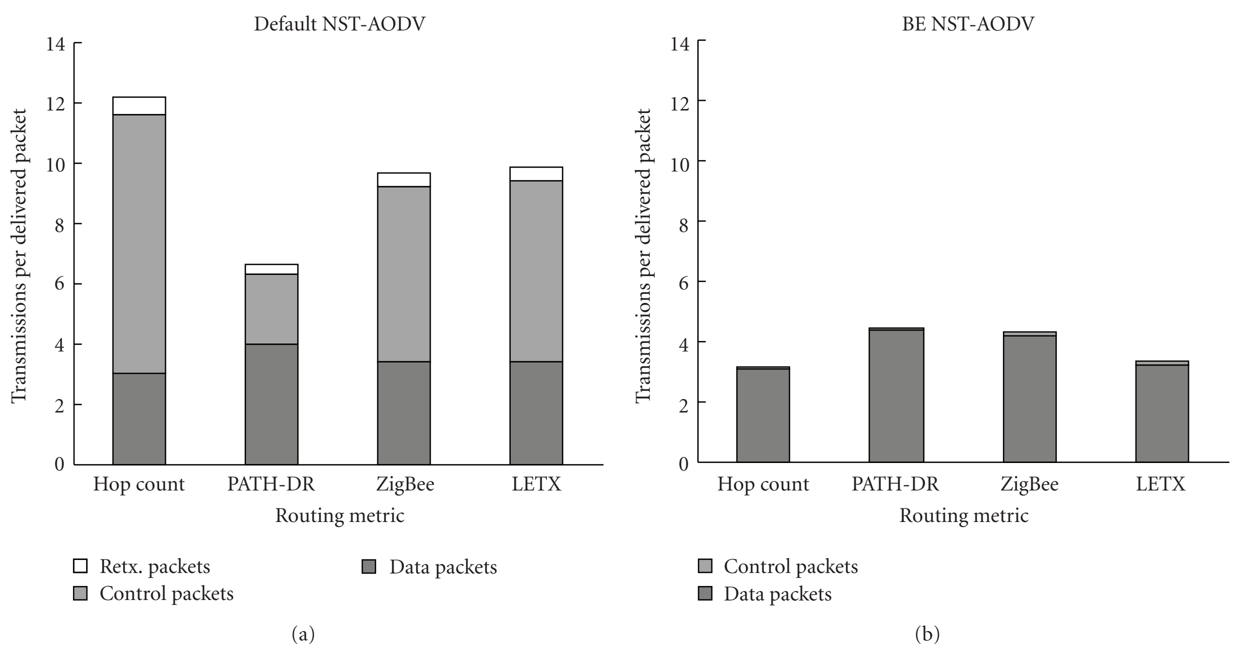


Figure 19: Average number of packet transmissions in the network per delivered packet for each routing metric, with default (a) and BE (b) NST-AODV.

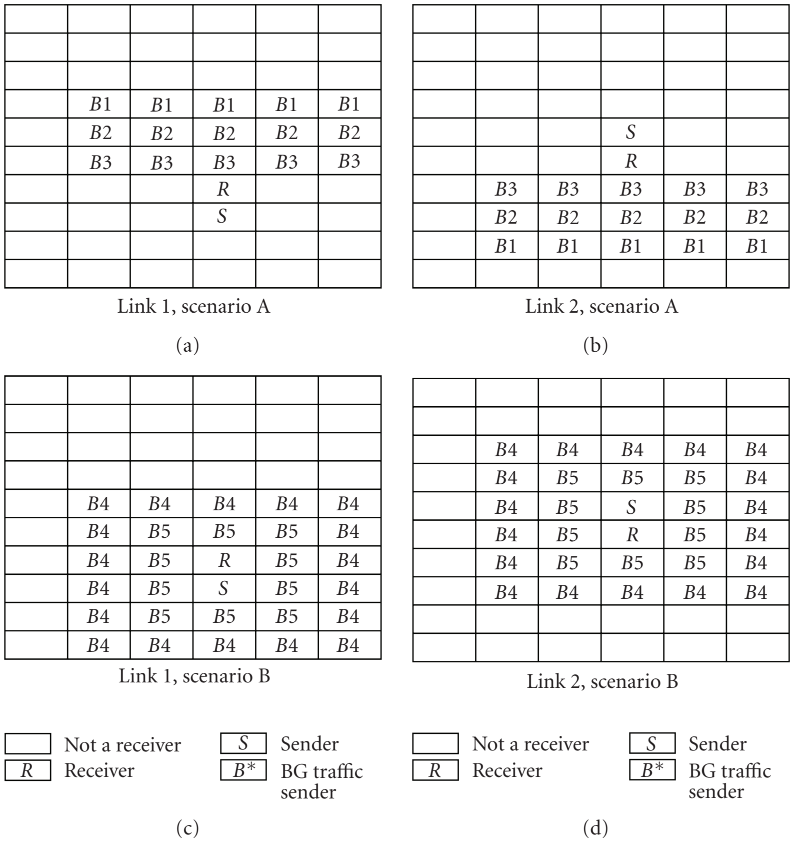


Figure 20: Testbed configurations for evaluating the sensitivity of LQI to background traffic.

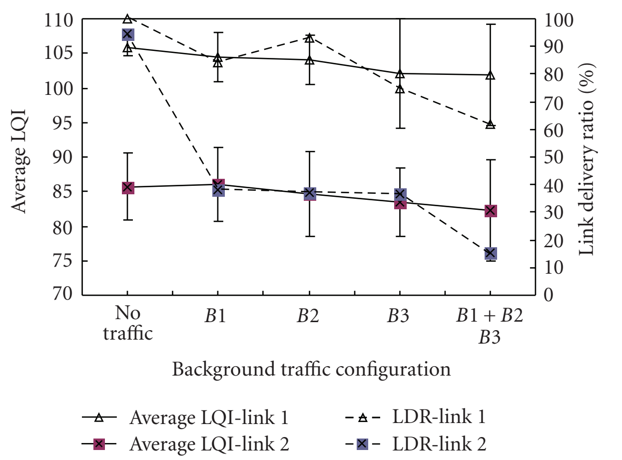


Figure 21: Influence of background traffic on LQI and LDR for two different links in scenario A. For the LQI, the standard deviation intervals are depicted.

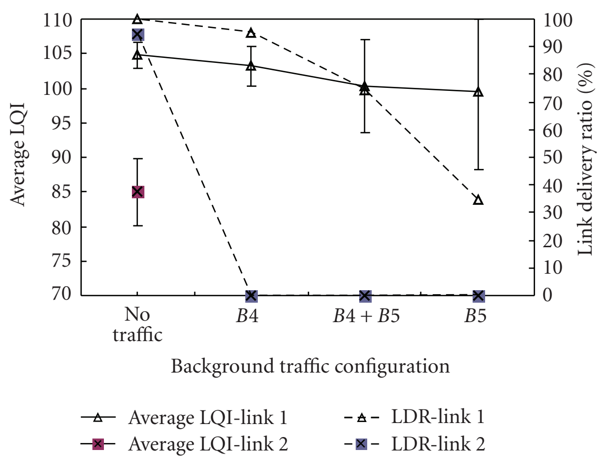


Figure 22: Influence of background traffic on LQI and LDR for two different links in scenario B. For the LQI, the standard deviation intervals are depicted.

Three different BG conditions were considered: (i) no BG traffic, (ii) B1 nodes transmitting BG traffic, and (iii) B2 nodes transmitting BG traffic. We decided to configure the nodes in the columns adjacent to those of the sender and receivers as routers-only, for a better evaluation of the paths selected in each case. For each routing metric, and for each receiver, one thousand packets were sent at a rate of 3 Hz.

Figures 24–26 show the PDR, the average path hop count and the cost of data packet delivery for each routing metric as a function of the background traffic conditions.

As shown in Figure 24, all LQI-based routing metrics outperform the Hop count metric in terms of PDR under all BG traffic conditions. The PDR decreases and the path hop count increases as the BG traffic transmitters are closer

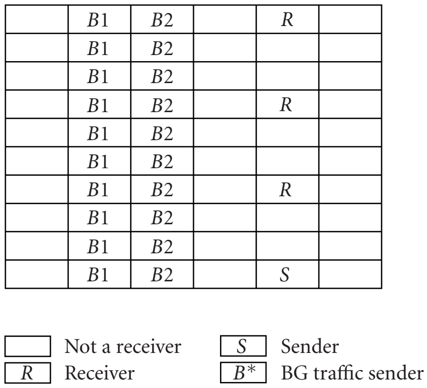


Figure 23: Background traffic scenario.

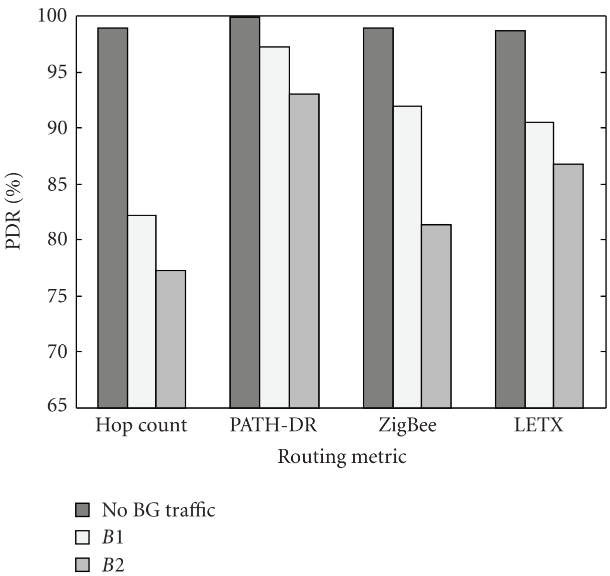


Figure 24: Impact of the routing metric on PDR, under various background traffic conditions.

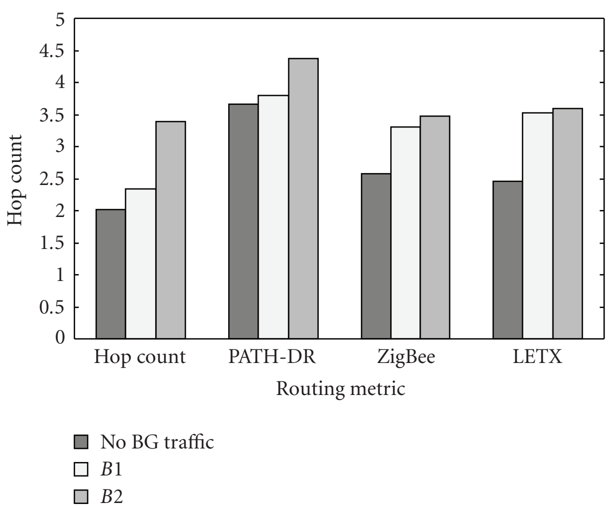


Figure 25: Impact of the Hop count metric on PDR, under various background traffic conditions.

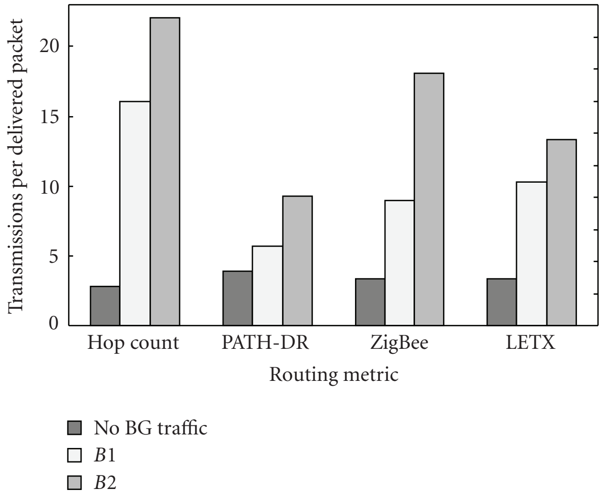


Figure 26: Average number of packet transmissions in the network per delivered packet for each routing metric, under different background conditions.

to the sender/receiver pair and as the interference level at the receiving end of each link becomes greater. PATH-DR yields the largest paths because it aims at maximizing the PDR, as we also observed in Section 7. The Hop count metric minimizes the path length. However, this metric selects paths that may not include good quality links and may be affected by BG traffic. LETX and ZigBee do not yield the same PDR as PATH-DR, but select shorter paths than those chosen by PATH-DR (see Figure 25).

As shown in Figure 26, in the absence of BG traffic, the PATH-DR metric gives the highest delivery cost. This happens because route failures do not happen often, and hence the number of control packet messages transmitted is low, which benefits the Hop count metric. However, under BG traffic conditions, LQI-based metrics, and in particular PATH-DR, outperform the Hop count metric. In fact, in these conditions, control packets due to route failure and discovery dominate the delivery cost, which benefits the metrics that provide good PDR.

9. Conclusions and Future Work

This paper presents an in-depth, experimental evaluation of LQI-based routing metrics for NST-AODV, which is a one-to-one routing protocol for IEEE 802.15.4 multihop networks.

From a characterization of the LQI, we conclude that a single LQI sample per link is sufficient for route discovery, since high-quality links provide stable LQI values and averaging the LQI for medium quality links does not assure reliable link estimation. The LQI values of route discovery messages are used to estimate link qualities, which are in turn the input for various routing metrics. The metrics considered are the Hop count (which does not take into account link quality), PATH-DR, ZigBee (link quality), and LETX metrics. The measurements were carried out in a 60-node test-bed over 52 different sender/receiver pairs. The influence of background traffic on the routing metrics was also tested.

Results show that PATH-DR obtains the highest PDR and maximizes path lifetime. The good performance of PATH-DR is due to the fact that it tends to select long paths composed of many robust links. LETX and ZigBee metrics are also sensitive to link quality and give a better performance than the Hop count metric, which selects the shortest paths regardless of their quality and suffers frequent path failures. However, both LETX and ZigBee are additive metrics, and therefore tend to select short paths, which may be composed of links that are not as robust as those used by PATH-DR.

With regard to minimizing the number of network transmissions per delivered packet, the best metric depends on the routing protocol settings. If a path failure triggers a route discovery procedure, then PATH-DR compensates its large paths with good stability. Otherwise, under a low rate of routing protocol messages, PATH-DR trades path stability for energy consumption.

The sensitivity of LQI to background traffic is low but sufficient, since the LQI-based routing metrics considered also perform well in the presence of background transmitters.

Although this study has been carried out using NST-AODV as the routing protocol, we believe that it will contribute to understanding the influence of LQI-based routing metrics for other routing paradigms for IEEE 802.15.4 multihop networks.

In future studies, we plan to evaluate the performance of LQI-based routing metrics in a network of battery-powered motes. According to preliminary results, the LQI values measured at a receiver decrease with the remaining energy level of the sender. In consequence, LQI-based routing metrics are also power-aware and can improve network lifetime.

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